US006487515B1

(12) **United States Patent**
Ghoshal

(10) **Patent No.: US 6,487,515 B1**
(45) **Date of Patent: Nov. 26, 2002**

(54) **METHOD AND APPARATUS FOR MEASURING THERMAL AND ELECTRICAL PROPERTIES OF THERMOELECTRIC MATERIALS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 128 days.

(21) Appl. No.: **09/641,662**

(22) Filed: **Aug. 18, 2000**

(51) **Int. Cl.**[7] **G01N 25/00**

(52) **U.S. Cl.** **702/136**; 374/45; 73/105; 136/228

(58) **Field of Search** 136/228, 203, 136/242; 438/455; 374/208; 347/8; 702/136; 73/105

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(57) **ABSTRACT**

A method and apparatus for measuring and characterizing microscopic thermoelectric material samples using scanning microscopes. The method relies on concurrent thermal and electrical measurements using scanning thermal probes, and extends the applicability of scanning thermal microscopes (SThMs) to the characterization of thermoelectric materials. The probe makes use of two thermocouples to measure voltages at the tip and base of a cone tip of the probe. From these voltages, and from a voltage measured across the sample material, the Seebeck coefficient, thermal conductivity and resistance of the sample material can be accurately determined.

34 Claims, 3 Drawing Sheets

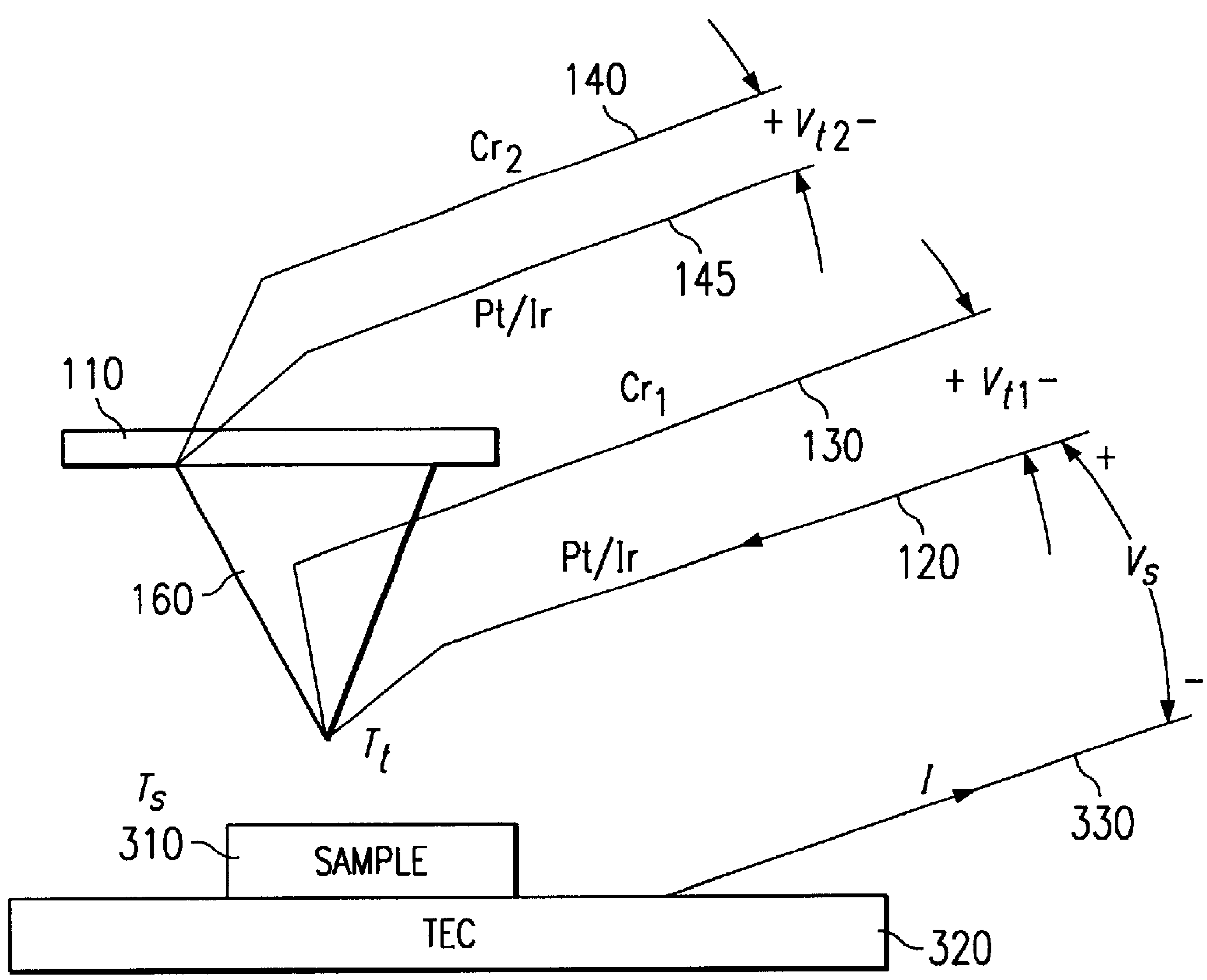


FIG. 1

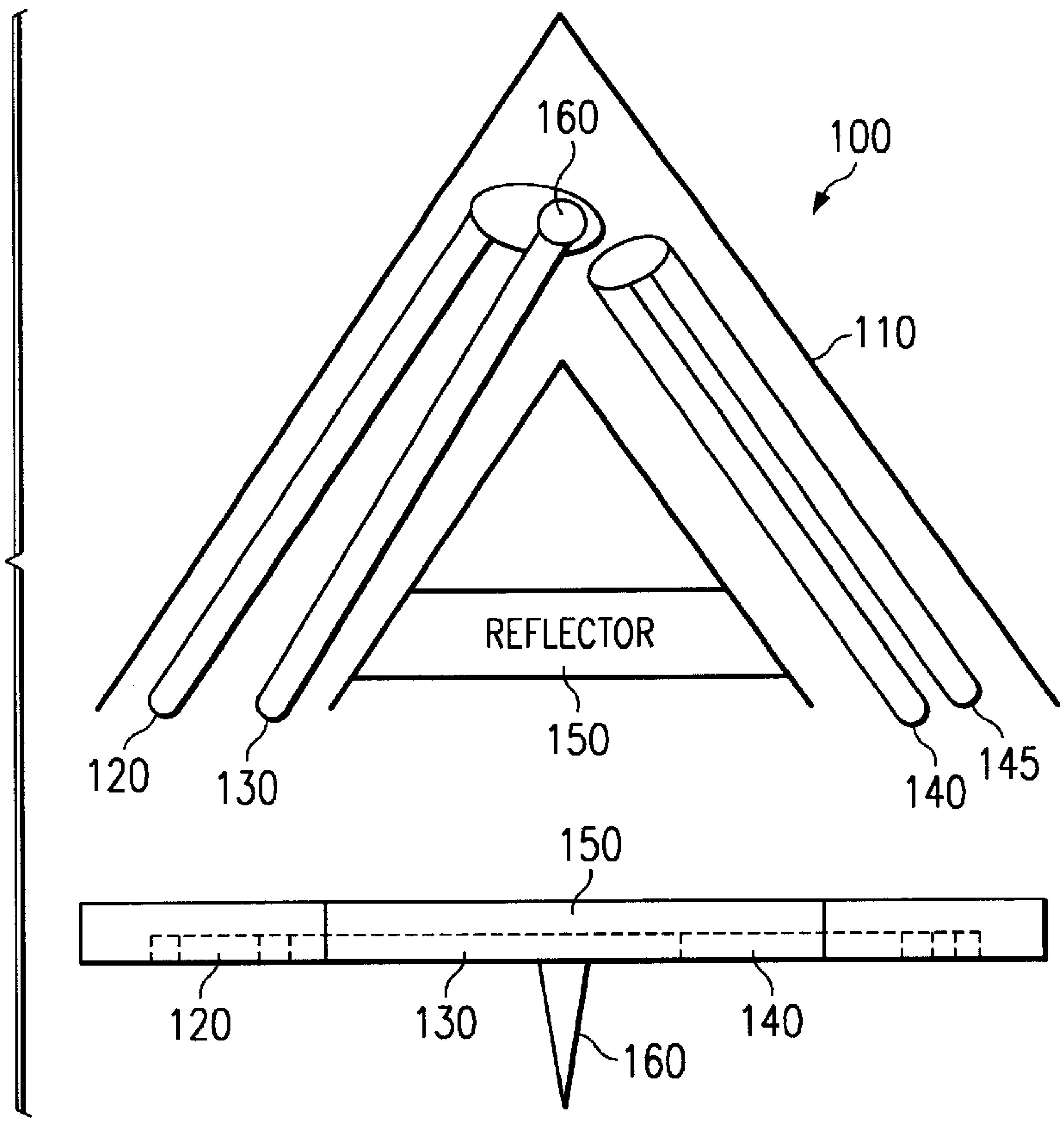


FIG. 2

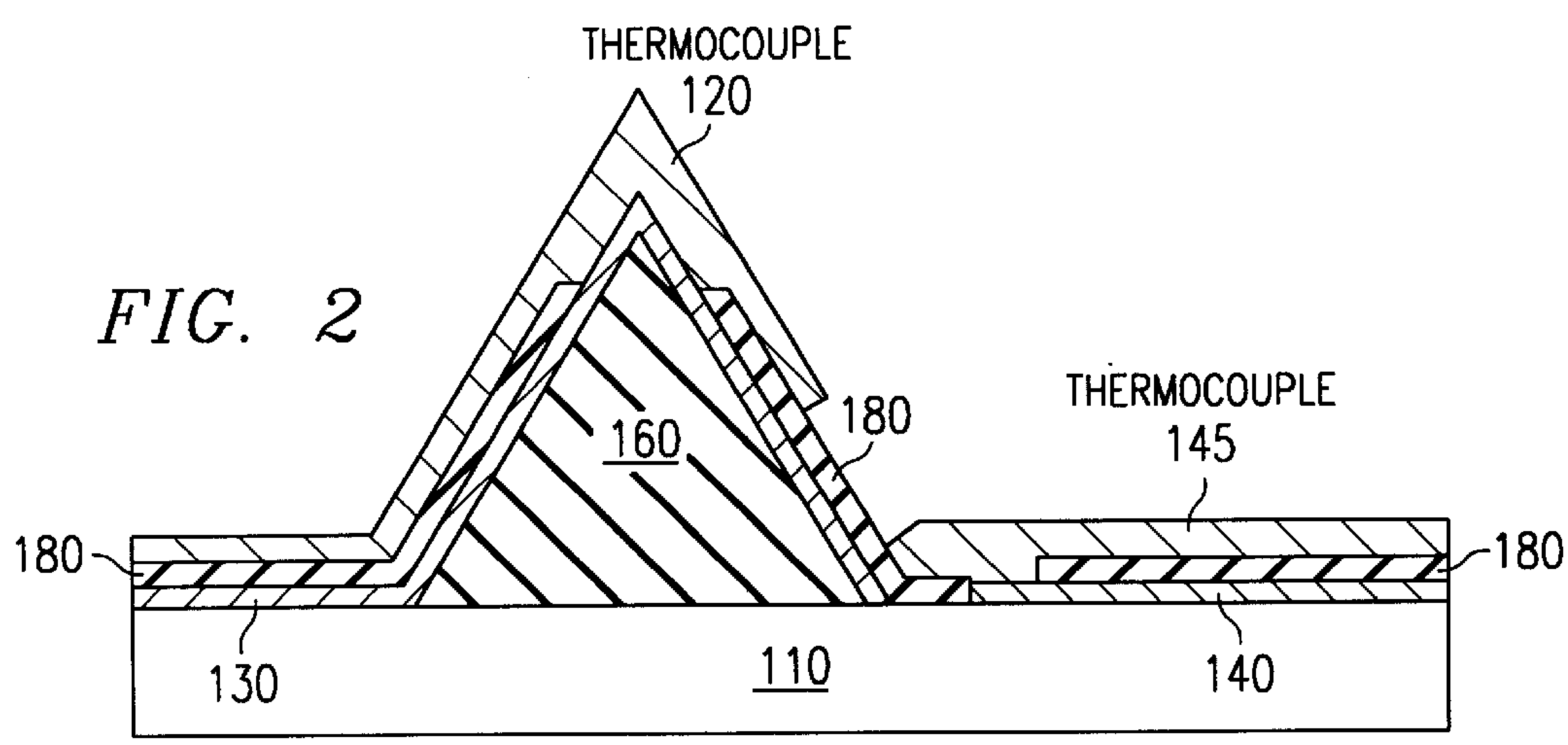
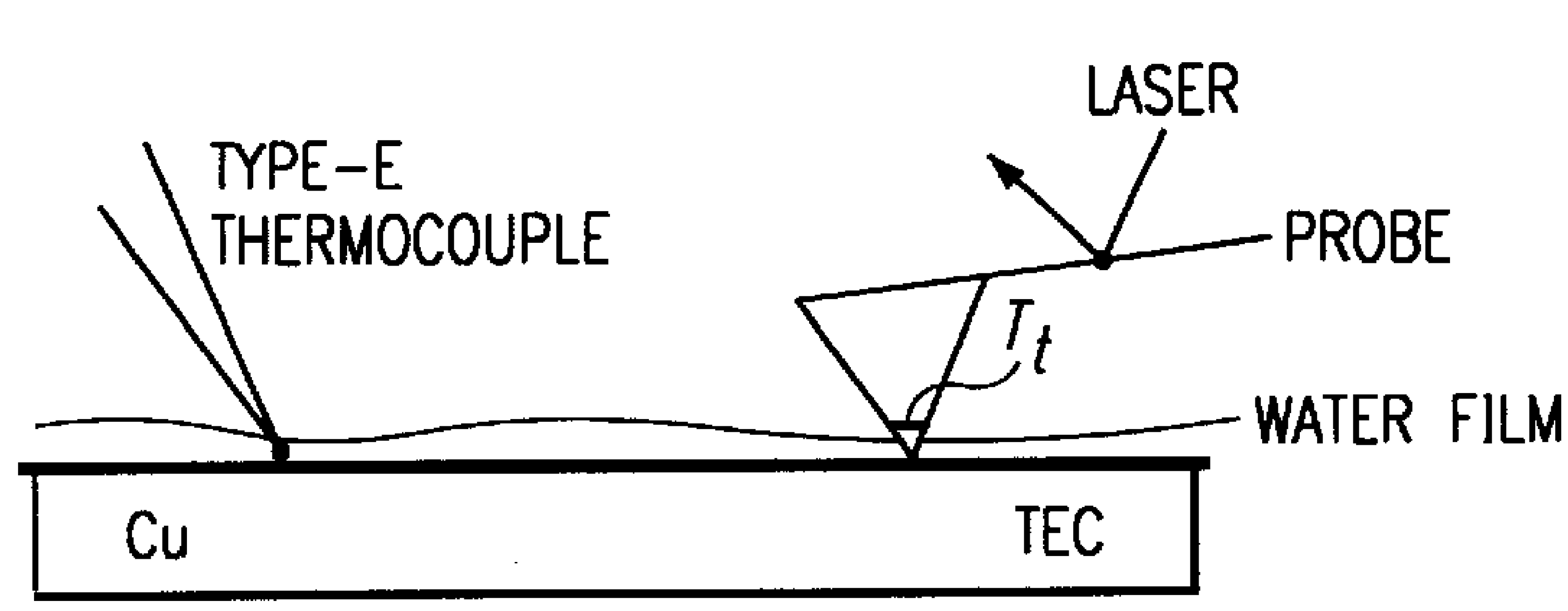


FIG. 6



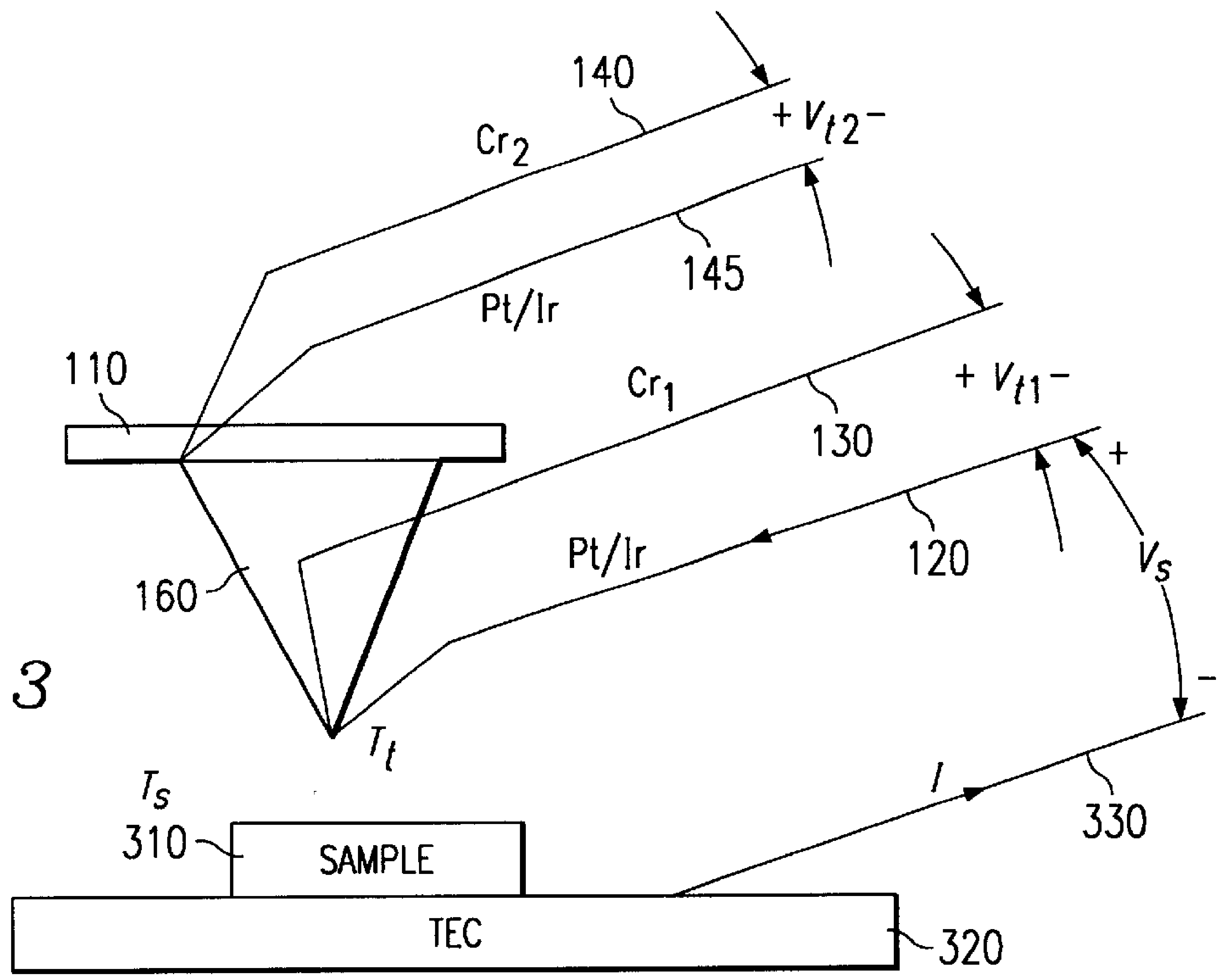


FIG. 3

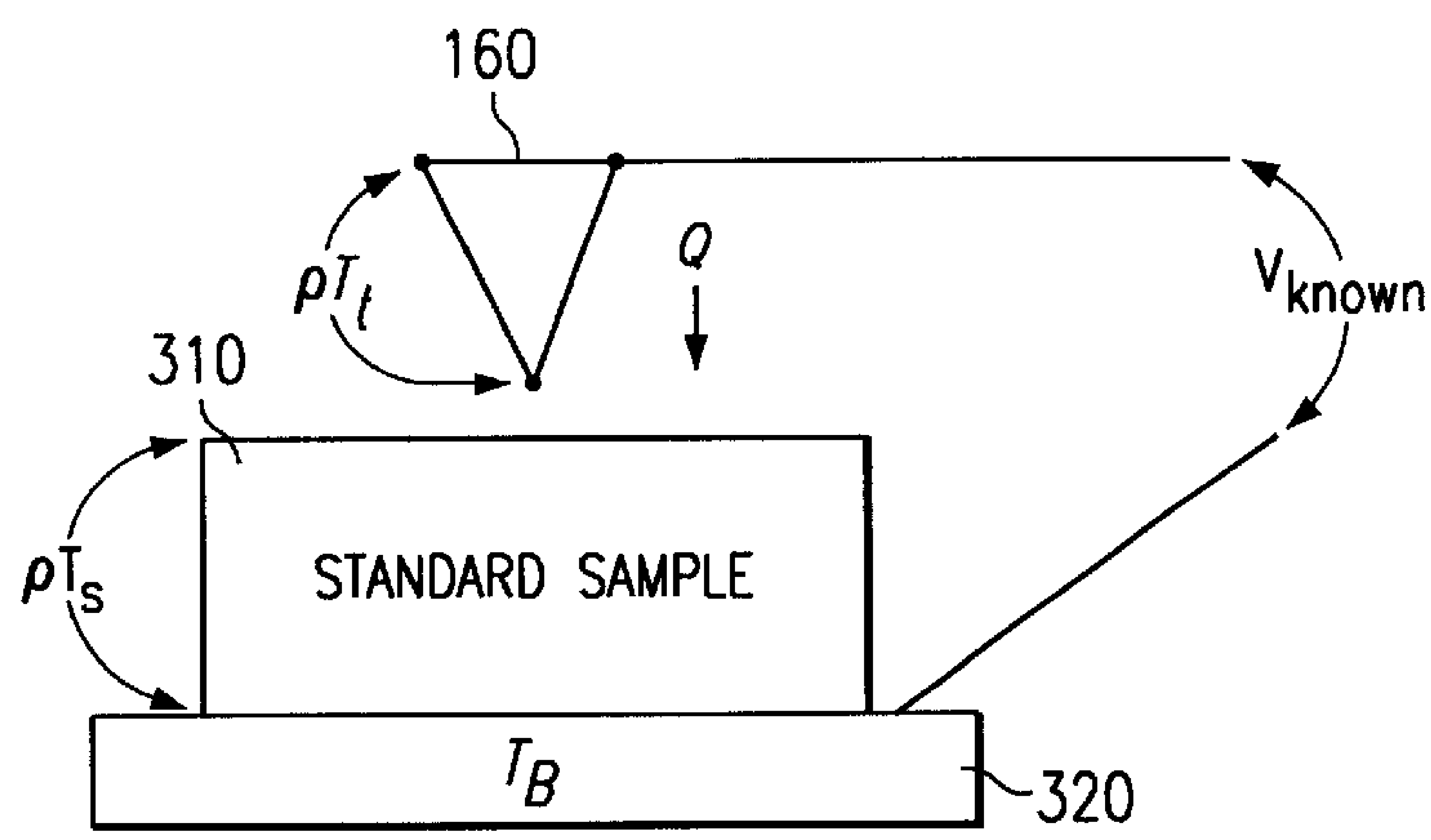


FIG. 4

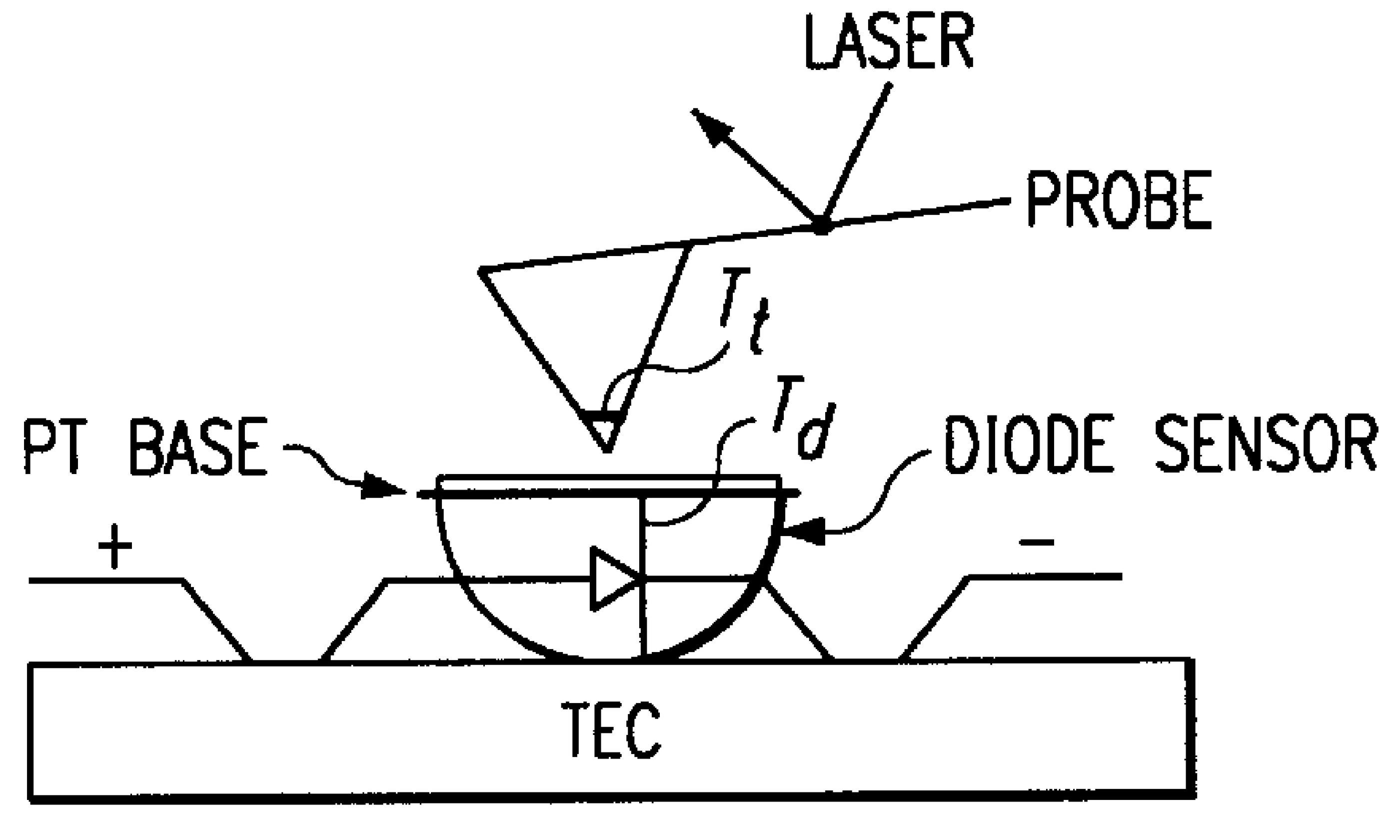


FIG. 5

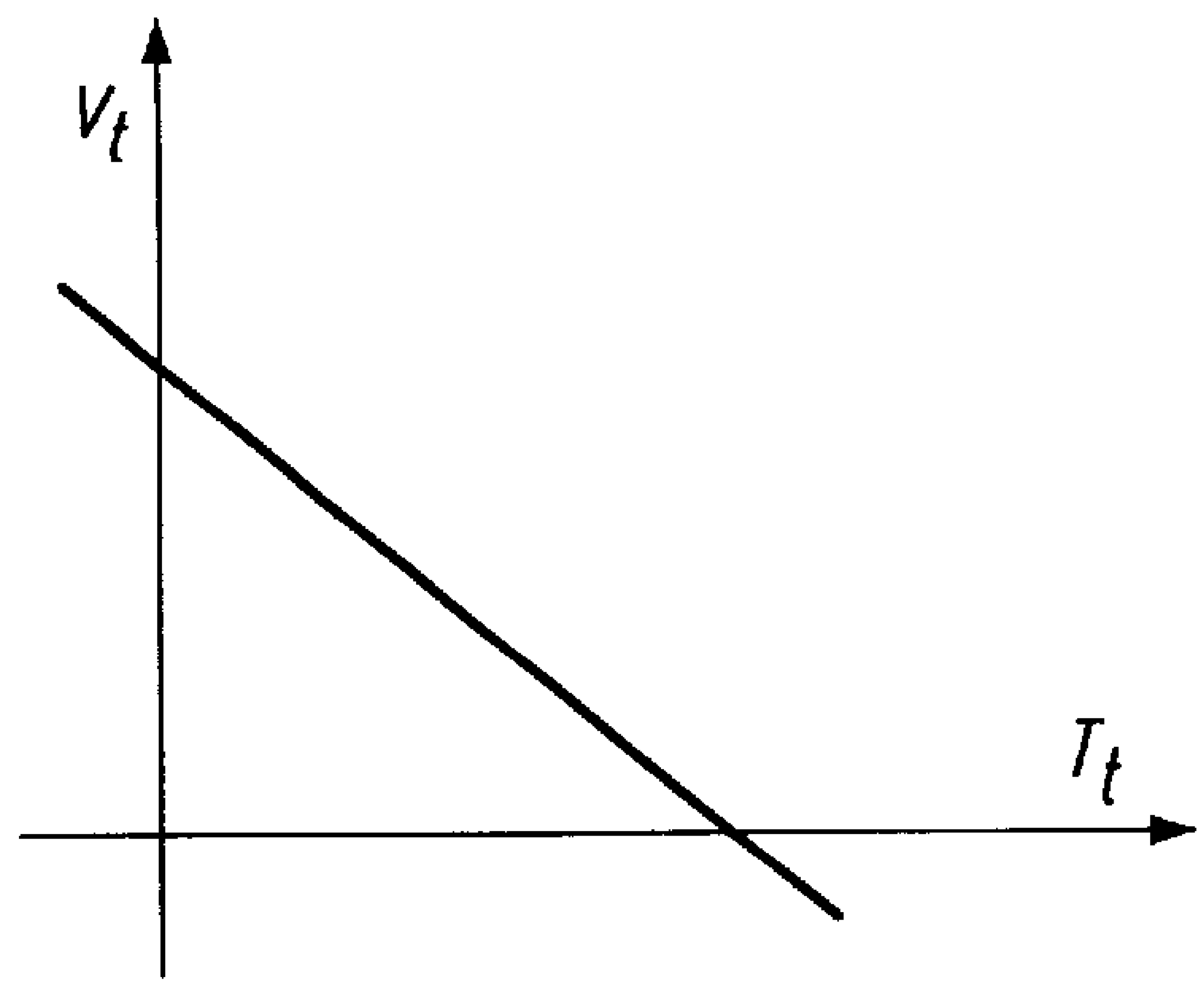


FIG. 7

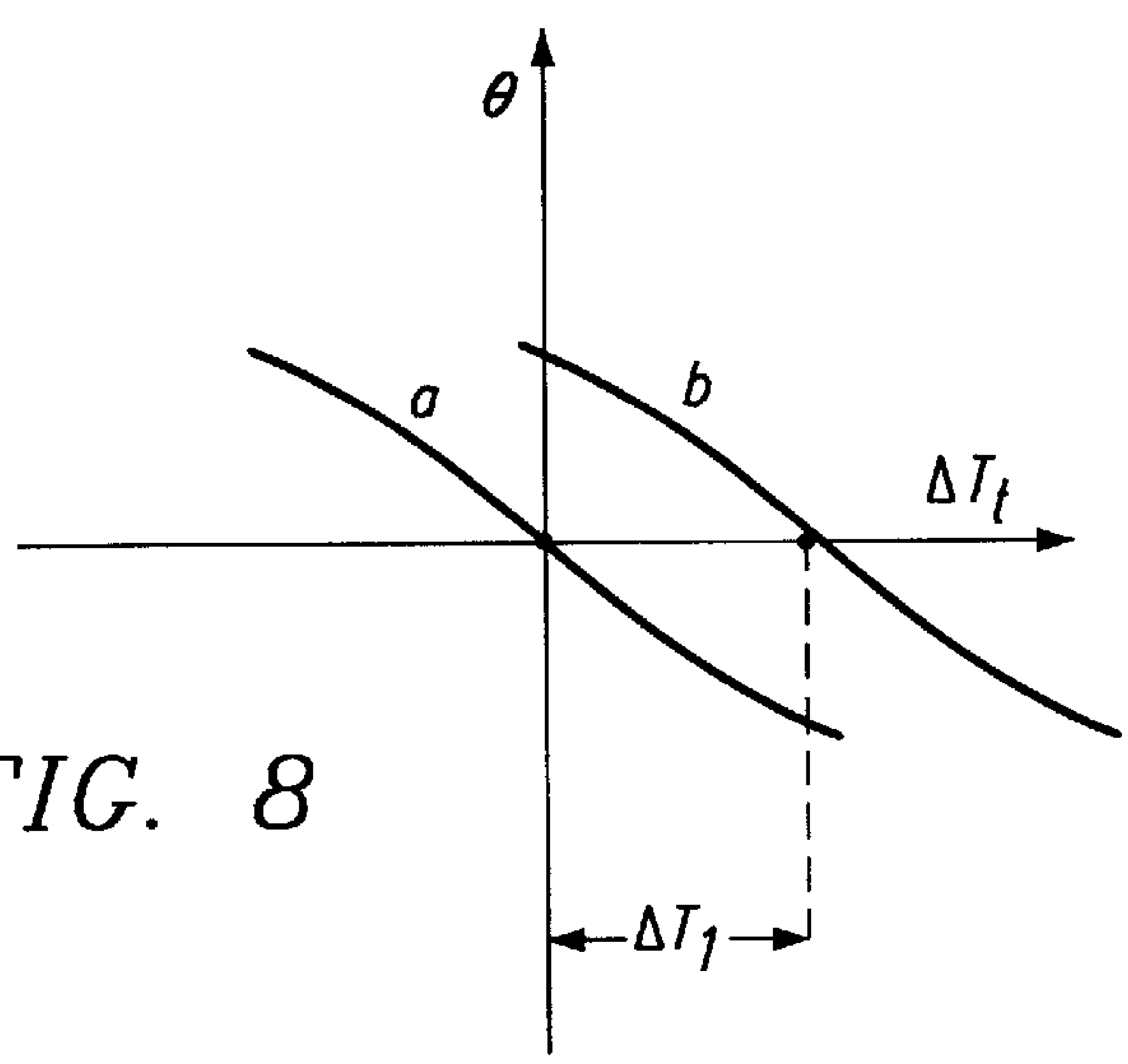


FIG. 8

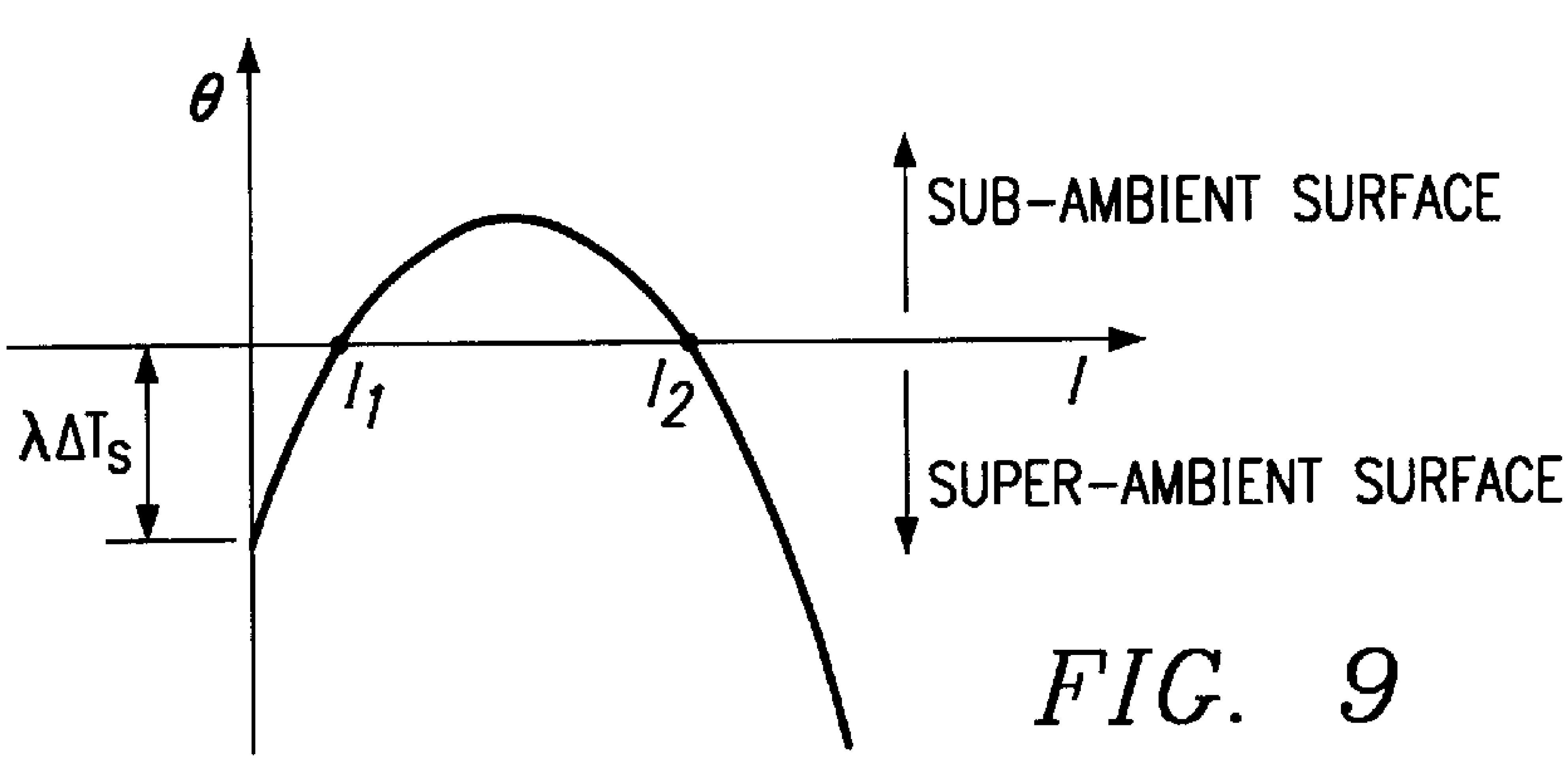


FIG. 9

METHOD AND APPARATUS FOR MEASURING THERMAL AND ELECTRICAL PROPERTIES OF THERMOELECTRIC MATERIALS

RELATED APPLICATIONS

The present application is related to commonly assigned and co-pending U.S. patent application Ser. No. 09/641,871 entitled "Probe Apparatus and Method for Measuring Thermoelectric Properties of Materials," which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

1. Technical Field

The present invention is directed to a method and apparatus for measuring thermal and electrical properties of thermoelectric materials.

2. Description of Related Art

One of the major difficulties in developing novel thin film thermoelectric materials lies in obtaining consistent and accurate measurement of their thermal and electrical properties. Traditional methods cannot be easily extended to microscopic characterization because of increased electrical and thermal parasitic losses associated with the probes used to perform the measurements. Additionally, the poor structural stability of some of the novel materials being investigated makes using traditional probe methods unworkable.

For example, in the case of measurements using a probe, such as the "ZT-meter," the time-scales of the transients become short and introduce errors in electrical measurements. Thus it would be beneficial to have an apparatus and method capable of performing measurements of thermal and electrical properties of thermoelectric materials in which the problems of the known methods with regard to thermal parasitic losses and structural stability of the thermoelectric materials, is overcome.

SUMMARY OF THE INVENTION

The present invention provides a method and apparatus for measuring and characterizing microscopic thermoelectric material samples using scanning atomic force microscopes. The methods rely on concurrent thermal and electrical measurements using scanning thermal probes, and extends the applicability of scanning thermal microscopes (SThMs) to the characterization of thermoelectric materials.

The probe of the present invention makes use of two temperature sensors, such as two thermocouples, to measure voltages at the tip and base of a cone tip of the probe. From these voltages, and from a voltage measured across the sample material, the Seebeck coefficient, thermal conductivity and resistance of the sample material can be accurately determined.

These thermoelectric properties may then be used in many different applications. For example, the thermoelectric properties may be used for characterization of scaled silicon devices wherein accurate spatial variation of Seebeck coefficient yields an exact dopant profiling with the silicon devices. Other features and advantages of the present invention will be described in or will become apparent to those of ordinary skill in the art in view of the following description of the preferred embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

FIG. **1** is an exemplary diagram illustrating a probe in accordance with the present invention;

FIG. **2** is an exemplary cross-sectional view of the probe in accordance with the present invention;

FIG. **3** is an exemplary circuit diagram illustrating the thermocouples of the probe;

FIG. **4** is an exemplary diagram illustrating the quantities used to perform temperature and heat flow calibration in accordance with the present invention;

FIGS. **5** and **6** are diagrams illustrating two methods of performing the calibration in accordance with the present invention;

FIG. **7** is an exemplary graph of voltage versus temperature at the tip of the probe, the relationship having been obtained from temperature calibration of the probe;

FIG. **8** is an exemplary graph of Θ versus temperature differential, the relationship having been obtained from heat flow calibration of the probe tip; and

FIG. **9** is an exemplary graph of Θ versus current for a material under test.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention provides a method and apparatus for measuring and characterizing the thermal and electrical properties of thermoelectric materials. The invention makes use of temperature sensors, such as thermocouple and thermistor probe style temperature sensors, designated for thermal probes and uses a surface electrode at the thermal probe tip for electrical measurements on a sample of the thermoelectric material.

The preferred embodiment of the present invention makes use of two thermocouples as the temperature sensors of the present invention. However, it should be appreciated that the present invention may use other types of temperatures sensors to measure the temperature values at various points on the probe without departing from the spirit and scope of the present invention. For example, rather than two thermocouples, the present invention may use one or more thermistors in place of or in addition to one or more of the thermocouples of the preferred embodiment. For purposes of illustration, however, the present invention will be described in terms of a probe having two therocouples which are used to measure temperature.

PROBE DESIGN

FIG. **1** is an exemplary diagram illustrating two views of a probe **100** in accordance with the present invention. The probe shown in FIG. **1** is used to measure the thermoelectric properties of thermoelectric materials in a manner described in detail hereafter. The probe in FIG. **1** makes use of two thermocouples to provide measurements of temperature that are then used to calculate thermoelectric properties of the thermoelectric material sample under test.

As shown in FIG. **1**, the probe **100** includes a cantilever substrate structure **110**, a first lead **120**, a second lead **130**, a third lead **140**, a fourth lead **145**, a reflector **150**, and a cone **160**. The leads **120–145** create two thermocouples which are used, in a manner to be described hereafter, to measure the temperature of the probe tip (cone **160** tip) and the temperature of a sample material. From these measurements, the thermoelectrical properties of the sample material may be determined.

The reflector **150** is used to reflect a laser beam toward a detector (not shown). The laser beam, reflector **150** and detector are used to measure the deflection of the cantilever structure **110** in order to maintain the distance between the probe tip **160** and the sample material at a constant value.

FIG. **2** is an exemplary cross section of the probe tip **160**. As shown in FIG. **2**, the probe tip **160** is comprised of a number of different layers of material. The particular materials described hereafter with reference to the exemplary embodiment are meant to be for illustrative purposes and other materials having similar properties may be used in replacement or in addition to the materials described herein without departing from the spirit and scope of the present invention.

The formation of the probe tip **160** will now be described with reference to FIG. **2**. The mechanisms used to create the various layers of the probe, such as deposition and etching, are generally known in the art of semiconductor chip manufacture. However, these mechanisms have not previously been used to create the structure herein described.

The cantilever substrate **110** is created first and is comprised of a silicon or silicon nitride material. A silicon oxide cone **160** is formed on the cantilever substrate **110**. A secondary metal layer is then created over the substrate **110** and the cone **160**. The secondary metal layer may be, for example, chromium, and is used to create the second lead **130** and third lead **140**.

It should be noted that the chromium layer does not cover all of the surface of the substrate **110** and cone **160**. Rather, as shown in FIG. **2**, a portion of the chromium layer at the base of the cone is etched away so that the two leads **130** and **140** are formed without touching one another.

Once the two leads **130** and **140** are created, a silicon oxide layer **180** is created on top of the chromium layer. The silicon oxide layer **180** is etched at the apex of the cone and at a point at the base of the cone to create two thermocouples which will be used in the present invention to perform thermoelectric property measurements of sample materials.

After the silicon oxide layer **180** is created, the primary metal layer **120** is created. The primary metal layer **120** is comprised of platinum/iridium in an exemplary embodiment, but may be any other type of metal which may be determined to have properties especially well suited for a particular application. As shown in FIG. **2**, the primary metal layer **120** is etched away at position near the base of the cone to thereby create the first and fourth leads **120** and **145**.

The interaction of the primary and secondary metal layers at the points where the silicon oxide layer **180** was etched away, creates the thermocouples which are used for measurements of thermoelectric properties. Additional layers of material may be added to the structure shown in FIG. **2** so long as these additional layers do not interfere with the operation of the dual thermocouples. For example, fine wires may be added to the cantilever structure **110** for heating the cantilever structure to thereby create a temperature differential, as will be described hereafter.

While the probe structure shown in FIGS. **1** and **2** show a cone-shaped probe tip, the probe tip may be of any shape desirable. For example, the cone-shaped probe tip may be vary narrow or very wide in diameter, may have any value interior angle at the tip, and the like. However, a narrower tip is preferable since the tip localizes measured temperature fields to a smaller area and thus, makes the probe capable of measuring thermoelectric properties of smaller scale materials.

The probe created using the process described above can be used for making measurements in many different applications. The probe may be used to measure thermoelectric properties of nano-scale structures, profiling of silicon dopants of semiconductor materials, characterizing giant magneto-resistive heads, and the like. The present invention is not limited to any one application of the probe and is intended to cover all possible applications to which the probe may be made.

Those of ordinary skill in the art will appreciate that the probe of the present invention is utilized along with a computing system in which the calibration and computations described hereafter are performed. The probe is used to provide measured quantities which are then processed by the computing system to calibrate the probe and generate values for the thermoelectric properties of the materials under test.

Calibration of the Probe

Before the probe can be used to measure the thermoelectric properties of sample materials, the probe must be calibrated. The calibration is performed using a sample whose thermoelectric properties are generally known in order to obtain a relationship of thermoelectric properties. The calibration method generally includes the steps of:

1) measuring the voltages across each of the thermocouples;

2) measuring the temperature from a bottom lead to the back side of the sample;

3) calibrating temperature according to NIST standards based on the above measurements; and

4) calibrating heat flow using the known thermoelectrical properties of the sample.

FIG. **3** shows a circuit schematic for a mixed mode operation probe in accordance with the present invention. As shown in FIG. **3**, the probe **100** consists of a first lead **120**, a second lead **130**, and a third lead **140**. The voltage V_{t1} across the first and second leads **120** and **130**, connected to the thermocouple at the tip **160**, are used to monitor the temperature and the heat flow out of the tip of the cone of the probe. The voltage V_{t2} across the third and fourth leads **140** and **145**, connected to the thermocouple at the base, are used to monitor the temperature and the heat flow at the base of the cone of the probe. Based on these voltages, the difference in temperature ΔT_t between the tip and base of the cone can be calculated. Current-voltage (I-Vs) measurements at the first and fifth leads **120** and **330** characterize the electrical properties of the thermoelectric material sample **310**.

The temperature sensors, i.e. thermocouples, at the tip may be calibrated in a number of different ways. In particular, the preferred embodiment of the present invention calibrates the temperature sensors at the tip by scanning the probe tip over a base of a pre-calibrated surface and over a metal surface of a thermoelectric cooler **320** concurrently. For example, the pre-calibrated material may be a platinum base of a pre-calibrated silicon diode mounted on the thermoelectric cooler and the metal surface may be a copper metal surface of the thermoelectric cooler **320**, as shown in FIG. **5**. In separate calibration, scanning a metal surface of a thermoelectric cooler may be concurrently monitored by a pre-calibrated E-type thermocouple, for example, as shown in FIG. **6**. Regardless of the particular manner by which calibration is performed, the method of temperature calibration is essentially the same.

The temperature sensors, i.e. thermocouples, at the tip and base of the cone **160** are used to measure voltage values for various tip and sample temperatures. With the present invention, a laser, which may be used may be used to detect cantilever deflection of the probe **100**, is switched OFF and the thermoelectric cooler **320** is activated to increase and decrease the temperature of the sample near the ambient.

Measurements of the voltages V_{t1} and V_{t2} are made using the thermocouples and are used to plot a relationship between the voltages and the temperature of the precalibrated surface. Using National Institute of Standards and Technology (NIST) temperature standards, a relationship of voltage to temperature is identified using known points. FIG. **7** shows an exemplary relationship between the tip voltage and the tip temperature. In this way, a one-to-one relation table between the thermocouple sensor voltage V and the temperature T may be obtained.

Although the above method is used in the preferred embodiment of the present invention, other methods of performing temperature calibration may be used with the present invention without departing from the spirit and scope of the present invention.

Once temperature calibration is performed, the thermocouple sensors must be calibrated for measurement of heat flow. The heat flow calibration makes use of a material having known thermoelectric properties. In particular, materials having known Seebeck coefficient α and thermal conductivity λ_k, are utilized.

FIG. **4** is an exemplary diagram that illustrates the basic method of heat calibration in accordance with the present invention. The heat flow Q from the tip to the sample surface is calibrated by scanning the probe tip in a contact-mode of operation over thermoelectric materials, such as $Bi_{0.5}Sb_{1.5}Te_3$, $Bi_2Te_{2.9}Se_{0.1}$, ZnSb, and Bi crystals, whose Seebeck coefficient α_{known} and thermal conductivity λ_{known} are known. The heat flow balance results in the following equation:

$$Q_p(\Delta T_t)=G\lambda_k\Delta T_s \tag{1}$$

where ΔT_s is the temperature drop across the sample and G is a geometric parameter. $G\approx 2\pi\alpha$ where α is the "thermal" radius of the probe tip. The value for ΔT_s equals the ratio of the voltage across the thermocouple between leads **120** and **140** and the Seebeck coefficient of the material (V/α). The open circuit voltage V_{known} is measured across leads **120** and **330**. Thus, the equation becomes:

$$\frac{Q_P(\Delta T_t)}{G}=\lambda_{known}(V_{known}/\alpha_{known}) \tag{2}$$

As shown in FIG. **8**, the quantity (Q_p/G), denoted by Θ, which is sometimes referred to as the normalized heat flow, can be tabulated for standard conditions, e.g., when the laser used for monitoring deflection is turned OFF (curve a) and turned ON (curve b). $\Theta=0$ at $T_t=0$ when the laser is OFF, and at $T_t=\Delta T_1$ when the laser is ON. Thus, from the temperature and heat flow calibrations above, the relationships V_t/T_t and $\Theta/\Delta T_t$ provide a complete thermoelectric calibration and characterization of the probe tip.

Thermoelectric Characterization of Materials

After calibration, the present invention may be used to thermally characterize thermoelectric materials. The method and apparatus of the present invention exploit the open-circuit condition: I=0. With the method and apparatus of the present invention, the tip voltage V_t and open-circuit voltage V_{so} are concurrently measured over the thermoelectric sample of unknown thermal conductivity λ and Seebeck coefficient a with a calibrated probe tip. T_b, the backside temperature of the sample, is varied by cooling the backside of the sample above and below the ambient. Alternatively, if there are heater wires provided in the cantilever structure **110**, the tip may be heated by passing high current through the heater wires. Any method of creating a temperature difference across the sample may be used without departing from the spirit and scope of the present invention. In doing so, the following relationship is obtained:

$$\lambda\Delta T_s=\frac{\lambda V_s}{\alpha}=\Theta(\Delta T_t) \tag{3}$$

where λ is an unknown thermal conductivity of the material and a is an unknown Seebeck coefficient of the material.

The ratio of the thermal conductivity of the material to its Seebeck coefficient can be measured precisely from equation (3), independent of the interface properties between the probe tip and the sample:

$$\frac{\lambda}{\alpha}=\frac{\Theta(\Delta T_t)}{V_s} \tag{4}$$

If either the thermal conductivity or the Seebeck coefficient is known, the other parameter can be accurately determined using the relationship above. This is especially useful, for example, when performing dopant profiling of silicon wafer chips. Since the thermal conductivity of silicon is a known value, measurements of the Seebeck coefficient by scanning the probe of the present invention across the chip, can be used to obtain an accurate profile of the dopants in the chip structure. In addition, these values can also be used to calculate the cooling capacity of thermoelectric coolers.

Electrical Characterization of Materials

The electrical characterization exploits the thermal isolation condition: $Q_p=0$ or $\Theta=0$. Under this condition, there is no temperature drop across the interface between the tip and the thermal sensor. The tip thermal sensor measures the temperature of the sample. An electric current is passed through the tip to attain this condition.

In the above example, the backside of the sample is maintained at temperature greater than the ambient temperature ($T_b>T_a$) so that $\Theta=\lambda\Delta T_s<0$ at I=0. The electric current I produces cooling at the contacts and results in the condition $\Theta=0$ and $T_t=T_s$ at $I=I_1$. If the current is increased further, the cooling effect increases and Θ attains a maximum when the surface temperature is such that the Joule heating balances the thermoelectric cooling effects. Further increase in I results in lower Θ and another $\Theta=0$ condition at $I=I_2$. The thermoelectric voltage ($\alpha\Delta T_s$) is the same at $I=I_1$ and $I=I_2$:

$$R+R_c=\frac{(V_{s2}-V_{s1})}{(I_2-I_1)}\quad\text{and} \tag{5}$$

-continued

$$\alpha = \frac{(I_2 V_{s1} - I_1 V_{s2})}{(I_2 - I_1)(T_b - T_t)} \tag{6}$$

where R is the resistance of the sample material and R_c is the electrical contact resistance of the contact between the probe and the sample material.

Alternatively (especially if the magnitude of the current I needs to be limited to small values for ultrathin films of the order of 100 nms), the Θ=0 can be obtained for two different values of T_b by changing the current of the external thermoelectric cooler. If the corresponding values of I are I_{01} and I_{02}, the I–V relations for the two cases are:

$$V_{s1}=I_{01}(R+R_c)+\alpha(T_t-T_{b1})$$

$$V_{s2}=I_{02}(R+R_c)+\alpha(T_t-T_{b2}) \tag{7}$$

Solving the simultaneous equations results in:

$$R + R_c = \frac{[(T_t - T_{b1})V_{s2} - (T_t - T_{b2})V_{s1}]}{[(T_t - T_{b1})I_{o2} - (T_t - T_{b2})I_{o1}]} \text{ and} \tag{8}$$

$$\alpha = \frac{(I_{o2}V_{s1} - I_{o1}V_{s2})}{[(T_t - T_{b1})I_{o2} - (T_t - T_{b2})I_{o1}]} \tag{9}$$

Once the Seebeck coefficient α is known, the thermal conductivity λ can be calculated using the equation (4). Moreover, the Seebeck coefficient and the resistivity of the sample material can be calculated using the above relationships and the following relationships relating to thermal conductance. With these thermoelectric properties of the sample material, the cooling performance of the sample material can be accurately determined.

Thermal Conductance

Although the thermal conductivity λ can be calculated independent of the thermal conductance of the element, it is important to extract the thermal conductance of the thermoelectric element for estimating the contact resistances. In order to extract the thermal conductance, let the temperature differential across the sample material be ΔT_s and the corresponding open-circuit voltage be $V_{so}=\alpha\Delta T_s$. One method to obtain the thermal conductance is to measure the differential change in electrical and thermal characteristics when the sample material is perturbed with a small current i about I=0. The heat balance conditions at the tip-sample surface for small positive-and negative-currents of magnitude i will be:

Cooling Mode:

$$Q(T_t+\delta T_t)=\alpha i(T_b+\Delta T_s-\delta T_s)-xi^2R-i^2R_c+K(\Delta T_s-\delta T_s) \tag{10}$$

Heating Mode:

$$Q(T_t+\delta T_t)=-\alpha i(T_b+\Delta T_s+\delta T_s)-xi^2R-i^2R_c+K(\Delta T_s+\delta T_s) \tag{11}$$

where δT_t and δT_s are the perturbations in tip temperature and sample surface temperature and x denotes the fraction of Joule heat generated in the thermoelement that flows back to the tip.

If $Q(T_t+\delta T_t)-Q(T_t-\delta T_t)=2\delta Q$, the following relation can be obtained based on equations (10) and (11):

$$\delta T_s = \frac{\alpha i(T_b + \Delta T_s) - \delta Q}{K} \tag{12}$$

The voltages across the thermoelement for positive and negative values of current are:

$$V_s+\delta V=i(R+R_c)+\alpha(\Delta T_s-\delta T_s)$$

$$V_s-\delta V=i(R+R_c)+\alpha(\Delta T_s+\delta T_s) \tag{13}$$

Hence, the differential voltage about the zero-current bias point can be given by:

$$\Delta T_s=i(R+R_c)-\alpha\delta T_s \tag{14}$$

Substituting the value of δT_s from equation (12) and noting that δQ/K=δΘ/λ results in a thermal resistance:

$$K = \frac{\alpha^2 i(T_b + \Delta T_s)}{\left[i(R + R_c) - \delta V - \left(\frac{\alpha}{\lambda}\right)\delta\Theta\right]} \tag{15}$$

Note that the relation is valid even for the particular case of $\Delta T_s=0$ and $T_b=T_a$. The conductance can thus be accurately estimated by measuring the amplitude of the variations of δV and δΘ for a sinusoidal/bipolar step variation of I.

Estimation of Contact Impedances

In the thermal characterization dealing with the open-circuit condition I=0, the heat flow through the tip to the sample surface is equal to the heat flow into the sample. This condition can be used to estimate the contact thermal resistance K_c.

$$Q=K_c(T_t-T_s)=K(T_s-T_b) \tag{16}$$

or,

$$K_c = K\left(\frac{\Delta T_s}{T_t - T_b - \Delta T_s}\right) = K\left(\frac{V_{so}/\alpha}{T_t - T_b - V_{so}/\alpha}\right)$$

Hence,

The electrical contact resistance R_c can be estimated by modeling the properties of the interface between the cone tip and the sample material. If it is assumed that the contact resistances are primarily electronic in nature and are related by a boundary form of the Wiedmann-Franzlaw, the following relation is obtain:

where $L_0 \sim (156\mu V/K)^2$ is the Lorentz number. Equations (5) and (8) can yield a value for the intrinsic thermoelement resistance if the contact resistance R_c is known.

It is important to note that while the present invention has been described in the context of a probe apparatus coupled to a fully functioning data processing system, those of ordinary skill in the art will appreciate that the processes of the present invention are capable of being distributed in the form of a computer readable medium of instructions and a variety of forms and that the present invention applies equally regardless of the particular type of signal bearing media actually used to carry out the distribution. Examples of computer readable media include recordable-type media, such as a floppy disk, a hard disk drive, a RAM, CD-ROMs, DVD-ROMs, and transmission-type media, such as digital and analog communications links, wired or wireless communications links using transmission forms, such as, for example, radio frequency and light wave transmissions. The computer readable media may take the form of coded formats that are decoded for actual use in a particular data processing system.

The description of the present invention has been presented for purposes of illustration and description, and is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art. The embodiment was chosen and described in order to best explain the principles of the invention, the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

What is claimed is:

1. A method of measuring thermoelectric characteristics of a material, comprising:

creating a temperature difference across the material;

measuring, with a probe, a voltage across the material;

measuring a difference in temperature between a tip of the probe and a base of the probe; and

calculating at least one thermoelectric characteristic based on the measured temperature difference and the measured voltage across the material.

2. The method of claim **1**, wherein creating a temperature difference across the material includes using a thermoelectric cooler at a base of the material to cool the material.

3. The method of claim **1**, wherein creating a temperature difference across the material includes passing a high current through a heater wire associated with the probe.

4. The method of claim **1**, wherein measuring a voltage across the material includes passing a current through a circuit comprising a lead to the tip of the probe and a lead to a base of the material.

5. The method of claim **1**, wherein measuring a difference in temperature between the tip of the probe and the base of the probe includes measuring a first voltage across a first thermocouple associated with the tip of the probe and measuring a second voltage across a second thermocouple associated with the base of the probe.

6. The method of claim **5**, wherein the difference in temperature is calculated based on a relationship of voltage at the tip to temperature at the tip and a relationship of heat flow across the probe to the difference in temperature across the probe.

7. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes determining a relationship of thermal conductivity to Seebeck coefficient.

8. The method of claim **7**, wherein the relationship of thermal conductivity to Seebeck coefficient is a ratio of a normalized heat flow, as a function of a voltage at the tip of the probe, to a voltage across the material.

9. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes determining a relationship of resistance of the material and a relationship of Seebeck coefficient of the material based on a voltage across the material, a current across the material, a temperature at the tip of the probe and a temperature at a back of the material for a condition where a normalized heat flow is zero.

10. The method of claim **9**, wherein the relationship of resistance of the material is:

where R is an electrical resistance of the material, R_c is an electrical resistance of an electrical contact between the tip of the probe and the material, I_{o1} is a current at a first cooling temperature T_{b1} where the normalize heat flow is zero, V_{s1} is a voltage across the material at the first cooling temperature, I_{o2} is a current at a second cooling temperature T_{b2} where the normalized heat flow is zero, V_{s2} is a voltage across the material at the second cooling temperature, and T_t is the temperature at the tip of the probe.

11. The method of claim **9**, wherein the relationship of Seebeck coefficient is

where I_{o1} is a current at a first cooling temperature T_{b1} where the normalize heat flow is zero, V_{s1} is a voltage across the material at the first cooling temperature, I_{o2} is a current at a second cooling temperature T_{b2} where the normalized heat flow is zero, V_{s2} is a voltage across the material at the second cooling temperature, and T_t is the temperature at the tip of the probe.

12. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes calculating a thermal resistance of the material based on a Seebeck coefficient of the material, a temperature drop across the material, a temperature of a back side of the material, a perturbation current, an electrical resistance of the material, an electrical resistance of a contact between the tip of the probe and the material, and a thermal conductivity of the material.

13. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes determining a thermal resistance of the material based on the relationship:

Where α is a Seebeck coefficient of the material, i is a small current, T_b is a temperature at a back of the material, ΔT_s is a temperature drop across the material, R is an electrical resistance of the material, R_c is an electrical resistance of a contact between the tip of the probe and the material, δV is a change in voltage, $\delta\Theta$ is a change in normalized heat flow, and λ is a thermal conductivity of the material.

14. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes determining an electrical resistance of a contact between the tip of the probe and the material as a function of the Lorentz number, temperature of the material and a thermal resistance at the contact.

15. The method of claim **1**, wherein calculating at least one thermoelectric characteristic includes determining an electrical resistance of a contact between the tip of the probe and the material using the relationship:

where L_o is the Lorentz number T_s is a temperature of the material, and K_c is thermal resistance at the contact.

16. The method of claim **1**, wherein measuring a difference in temperature between the tip of the probe and the base of the probe includes measuring the temperature at the tip of the probe using a first temperature sensor and measuring the temperature at the base of the probe using a second temperature sensor.

17. The method of claim **16**, wherein at least one of the first temperature sensor and the second temperature sensor is one of a thermocouple and a thermistor.

18. A computer program product in a computer readable medium for measuring thermoelectric characteristics of a material, comprising:

first instructions for creating a temperature difference across the material;

second instructions for measuring, with a probe, a voltage across the material;

third instructions for measuring a difference in temperature between a tip of the probe and a base of the probe; and

fourth instructions for calculating at least one thermoelectric characteristic based on the measured temperature difference and the measured voltage across the material.

19. The computer program product of claim **18**, wherein the first instructions for creating a temperature difference across the material include instructions for using a thermoelectric cooler at a base of the material to cool the material.

20. The computer program product of claim **18**, wherein the first instructions for creating a temperature difference across the material include instructions for passing a high current through a heater wire associated with the probe.

21. The computer program product of claim **18**, wherein the second instructions for measuring a voltage across the material include instructions for passing a current through a circuit comprising a lead to the tip of the probe and a lead to a base of the material.

22. The computer program product of claim **18**, wherein the third instructions for measuring a difference in temperature between the tip of the probe and the base of the probe include instructions for measuring a first voltage across a first thermocouple associated with the tip of the probe and measuring a second voltage across a second thermocouple associated with the base of the probe.

23. The computer program product of claim **22**, wherein the difference in temperature is calculated based on a relationship of voltage at the tip to temperature at the tip and a relationship of heat flow across the probe to the difference in temperature across the probe.

24. The computer program product of claim **18**, wherein the fourth instructions for calculating at least one thermoelectric characteristic include instructions for determining a relationship of thermal conductivity to Seebeck coefficient.

25. The computer program product of claim **24**, wherein the relationship of thermal conductivity to Seebeck coefficient is a ratio of a normalized heat flow, as a function of a voltage at the tip of the probe, to a voltage across the material.

26. The computer program product of claim **18**, wherein the fourth instructions for calculating at least one thermoelectric characteristic include instructions for determining a relationship of resistance of the material and a relationship of Seebeck coefficient of the material based on a voltage across the material, a current across the material, a temperature at the tip of the probe and a temperature at a back of the material for a condition where a normalized heat flow is zero.

27. The computer program product of claim **18**, wherein the fourth instructions for calculating at least one thermoelectric characteristic include instructions for calculating a thermal resistance of the material based on a Seebeck coefficient of the material, a temperature drop across the material, a temperature of a back side of the material, a perturbation current, an electrical resistance of the material, an electrical resistance of a contact between the tip of the probe and the material, and a thermal conductivity of the material.

28. The computer program product of claim **18**, wherein the fourth instructions for calculating at least one thermoelectric characteristic include instructions for determining an electrical resistance of a contact between the tip of the probe and the material as a function of the Lorentz number, temperature of the material and a thermal resistance at the contact.

29. An apparatus for measuring thermoelectric characteristics of a material, comprising:

a means for creating a temperature difference across the material; and

a probe for measuring a voltage across the material and for measuring a difference in temperature between a tip of the probe and a base of the probe, wherein at least one thermoelectric characteristic is determined based on the measured temperature difference and the measured voltage across the material.

30. The apparatus of claim **29**, further comprising a computer for determining the at least one thermoelectric characteristic.

31. The apparatus of claim **30**, wherein the at least one thermoelectric characteristic is determined using a relationship of thermal conductivity to Seebeck coefficient.

32. The apparatus of claim **30**, wherein the at least one thermoelectric characteristic is determined based on a relationship of resistance of the material and a relationship of Seebeck coefficient of the material based on a voltage across the material, a current across the material, a temperature at the tip of the probe and a temperature at a back of the material for a condition where a normalized heat flow is zero.

33. The apparatus of claim **29**, wherein the probe includes a first temperature sensor for measuring the temperature at the tip of the probe and a second temperature sensor for measuring the temperature at the base of the probe.

34. The apparatus of claim **33**, wherein at least one of the first temperature sensor and the second temperature sensor is one of a thermocouple and a thermistor.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : 6,487,515 B1
DATED : November 26, 2002
INVENTOR(S) : Ghoshal

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 9,
Line 62, please begin a new line and insert

-- $$R+R_c = \frac{[(T_r-T_{b1})V_{s2}-(T_r-T_{b2})V_{s1}]}{[(T_r-T_{b1})I_{o2}-(T_r-T_{b2})I_{o1}]}$$ --

Column 10,
Line 8, please begin a new line and insert

-- $$a = \frac{(I_{o2}V_{s1}-I_{o1}V_{s2})}{[(T_r-T_{b1})I_{o2}-(T_r-T_{b2})I_{o1}]}$$ --

Line 26, please begin a new line and insert

-- $$K = \frac{a^2 i(T_b+\Delta T_s)}{[i(R+R_c)-\delta V-(\frac{a}{\lambda})\delta\Theta]}$$ --

Line 44, please begin a new line and insert

-- $$R_c = \frac{L_0 T_s}{K_c}$$ --

Signed and Sealed this

Fifth Day of August, 2003

JAMES E. ROGAN
Director of the United States Patent and Trademark Office